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Concentrations of volatile organic compounds, carbon monoxide, carbon dioxide and particulate matter in buses on highways in Taiwan

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ABSTRACT

Although airborne pollutants in urban buses have been studied in many cities globally, long-distance buses running mainly on highways have not been addressed in this regard. This study investigates the levels of volatile organic compounds (VOCs), carbon monoxide (CO), carbon dioxide (CO_2) and particulate matter (PM) in the long-distance buses in Taiwan. Analytical results indicate that pollutants levels in long-distance buses are generally lower than those in urban buses. This finding is attributable to the driving speed and patterns of long-distance buses, as well as the meteorological and geographical features of the highway surroundings. The levels of benzene, toluene, ethylbenzene and xylene (BTEX) found in bus cabins exceed the proposed indoor VOC guidelines for aromatic compounds, and are likely attributable to the interior trim in the cabins. The overall average CO level is 2.3 ppm, with higher average level on local streets (2.9 ppm) than on highways (2.2 ppm). The average CO_2 level is 1493 ppm, which is higher than the guideline for non-industrial occupied settings. The average PM level in this study is lower than those in urban buses and IAQ guidelines set by Taiwan EPA. However, the average PM_{10} and $PM_{2.5}$ is higher than the level set by WHO. Besides the probable causes mentioned above, fewer passenger movements and less particle re-suspension from bus floor might also cause the lower PM levels. Measurements of particle size distribution reveal that more than 75% of particles are in submicron and smaller sizes. These particles may come from the infiltration from the outdoor air. This study concludes that air exchange rates in long-distance buses should be increased in order to reduce CO_2 levels. Future research on long-distance buses should focus on the emission of VOCs from brand new buses, and the sources of submicron particles in bus cabins.

1. Introduction

A vehicle cabin is an important microenvironment leading to passenger exposure to elevated levels of air pollutants, such as volatile organic compounds (VOCs), carbon monoxide (CO), carbon dioxide (CO_2) and particulate matter (PM) (Lau and Chan, 2003; Chan, 2005; Behrentz et al., 2005; Parra et al., 2008; Rim et al., 2008). Among VOCs affecting human health, traffic-related emissions are well known to contain benzene, toluene, ethylbenzene and m-, p- and o-xylene isomers (Batterman et al., 2002), and many other compounds such as aldehydes (Jo and Lee, 2002). Additionally, excess intake of CO, a colorless, odorless and tasteless compound, inhibits the oxygen-carrying capability of hemoglobin. Exposure to CO in vehicular microenvironments has become a cause for rising concern over the past decade (Gómez-Perales et al., 2007). The level of CO_2 is used to measure the air freshness (WHO, 2005). Epidemiological studies have confirmed a strong relationship between exposure to inhalable particles and respiratory diseases, as well as cardiovascular morbidity and mortality (Koskela et al., 2005). Therefore, several studies have been performed in many cities around the world to examine the in-vehicle levels of VOCs (Batterman et al., 2002; Chan et al., 2003; Lau and Chan, 2003; Parra et al., 2008), CO (Chan et al., 1999, 2002a,b; Duci et al., 2003; Chan, 2005), CO_2 (Chan, 2005) and PM (Praml and Schierl, 2000; Adams et al., 2001; Gómez-Perales et al., 2007; Kaur et al., 2007; Hertel et al., 2008).

Among all forms of road transport, buses have received much more attention than taxis or private cars, because more passengers are exposed to indoor airborne pollutants in buses, which provide more convenient access within urban areas. In addition to some studies targeting public buses, a few studies have been conducted in Los Angeles, US to characterize the exposure to air pollutants among children during school bus commutes (Behrentz et al., 2005; Marshall and Behrentz, 2005). Although levels of in-vehicle pollutants inside buses have been reported, these have largely been from urban buses with stop-and-go driving patterns. In contrast to the buses in urban areas, long-distance buses are characterized by long

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travel time, high speed and long time on highways. Additionally, highway traffic conditions and surroundings differ from those on local routes. Air pollutants in long-distance buses have not been examined to date, and therefore need to be addressed. This study investigated the levels of VOCs, CO, CO_2 and PM in the long-distance buses traveling along the west corridor of Taiwan. The long-distance buses in Taiwan are very different from the buses commonly seen on local streets, typically having a lavatory and six to eight 15″ TV sets in cabin. The sofa-type seats are like those in the first-class cabin of airliners, therefore, leading to a seat capacity of only about 20. The seats in one bus company even have a massage function and personal LCD TV. The interior trim in cabins and highway traffic conditions and surroundings mean that the levels of air pollutants in long-distance buses are noteworthy. In contrast to other recent studies, this study presents the pollution levels in the buses running on local streets as well as highways. The factors that affect the measured pollutant levels in bus cabins are also discussed.

2. Experimental methods

2.1. Sampling design

Three bus companies providing passenger transport service between Tainan City and Taipei City were recruited for this study in the period between February, 2006 and June, 2006. Tainan, the fourth largest city in Taiwan locating in southern Taiwan, has a population of 750,000 people. The total population in this area, including the populations of nearby satellite towns, is up to 1.5 million people. Taipei, the capital of Taiwan locating in the north, is the center of a metropolitan area with a population of more than 6.5 million people. Three round-trip journeys (i.e., six one-way journeys) from two companies, and two round-trip journeys from the third company, were randomly selected for air sampling. A total of 16 air samplings were performed in the present study and the characteristics of the 16 buses selected are summarized in Table 1. To avoid extremely large traffic volume and slower driving speed over weekends and holidays, all samplings were conducted during weekdays. In-cabin air samples were taken between departure from the terminal in one city and the arrival at the terminal in another city. After departure in one city, those buses first drove on local streets before traveling on the highway, then drove on local streets again after exiting the highway towards the terminal in the next city. Fig. 1 shows a schematic map of the highway connecting Taipei and Tainan, and the map of bus routes on local streets. The total traveling distance was approximately 300 km, which normally took 4 to 5 h, depending on traffic and weather conditions. For a one-way journey between two cities, approximately 15%–20% of traveling time was spent on local streets. Indoor temperature was automatically controlled by an air-conditioning system while driving, and all windows remained closed. Information such as in-cabin temperature and relative humidity, number of passengers, number of door opening for passenger boarding and alighting on local streets, driver and passengers activities and traffic conditions were recorded. The buses measured in this study were 2.7 years old on average, and were all powered by diesel fuel. All the buses were about the same size, 12 m in length, 2.4 m in width and 3.3 m in height. The average traveling time between two cities was 4 h and 23 min. A journey carried 14 passengers on average.

Table 1
Characteristics of buses studied.

Buses	Date (North/South bound)	Engine type	Service year	Passenger Number	Cabin temperature, °C and RH, % (s.d.)
1	2006/2/17 (N)	Doosan	2	9	21.5 (1.0); 67.9 (4.5)
2	2006/2/17 (S)	Doosan	2	16	22.6 (0.7); 63.9 (2.1)
3	2006/3/6 (N)	Doosan	1	10	23.2 (1.0); 66.7 (8.0)
4	2006/3/6 (S)	Doosan	3	10	24.4 (0.7); 61.3 (6.7)
5	2006/4/6 (N)	Doosan	2	14	24.7 (0.8); 72.5 (6.0)
6	2006/4/6 (S)	Doosan	3	12	23.6 (0.4); 60.1 (2.4)
7	2006/4/7 (N)	DDEC II	3	12	23.7 (0.9); 62.5 (13.7)
8	2006/4/7 (S)	DDEC II	2	14	24.4 (1.7); 47.6 (10.3)
9	2006/4/13 (N)	DDEC II	3	10	23.7 (1.6); 43.3 (6.8)
10	2006/4/14 (S)	DDEC II	3	11	25.6 (1.7); 47.1 (7.5)
11	2006/6/9 (N)	DDEC II	3	9	23.3 (0.7); 67.1 (9.0)
12	2006/6/9 (S)	DDEC II	2	15	21.9 (1.6); 66.2 (15.9)
13	2006/3/15 (N)	Cummins	3	15	26.3 (0.7); 48.2 (6.4)
14	2006/3/15 (S)	Cummins	4	19	24.2 (1.1); 64.5 (6.7)
15	2006/4/27 (N)	Cummins	4	17	24.4 (3.1); 55.1 (11.1)
16	2006/5/1 (S)	Cummins	3	18	23.5 (1.4); 64.4 (5.3)

2.2. Air sampling and analysis

Concentrations of benzene, toluene, ethylbenzene and m/p-xylene, o-xylene (BETX), formaldehyde, CO, CO_2, PM_{10} and $PM_{2.5}$ were measured in all 16 one-way journeys. Samples of VOCs were collected using a low-flow SKC Model 222 sampling pump (SKC Inc., Eighty Four, PA, US) connected to stainless steel tubes (Perkin Elmer Ltd., Beaconsfield, UK) packed with 250 mg Tenax-TA 60/80 mesh. Each tube was sampled at a flow rate of 200 mL min^{-1} for 2 h, and two or three tubes were needed for each one-way journey, depending on traveling time. The samples were desorbed using a Perkin-Elmer ATD 400 at 300 °C for 10 min. The sampled air was then analyzed with an Agilent 6890 Gas Chromatography/Flame Ionization Detector (GC/FID) (Agilent Inc. Santa Clara, CA, US). Concentrations of formaldehyde were measured by a formaldemeter (PPM Technology, Caernarfon, UK). A TSI model 8554 Q-Trak (St. Paul, MN, US) was used to measure CO and CO_2 levels, while PM_{10} and $PM_{2.5}$ were measured by using TSI model 8520 DustTrak aerosol monitors with a PM_{10} and $PM_{2.5}$ inlet, respectively. The PM_{10} and $PM_{2.5}$ readings were further corrected according to the calibration equations obtained from the same authors. The details of the calibration experiments can be seen in the work by Huang and Hsu (2009). Data from both Q-trak and DustTrak were recorded on average every minute, and were recorded in a data logger. The size distribution of airborne particles was measured by a TSI model 3320 Aerodynamic Particle Sizer (APS) in four journeys. Due to the limited battery power, APS was operated for 30 min in every hour during the journey. These sampling instruments were all placed in the center of the bus cabins, and at the height of the breathing zone of seated passengers.

2.3. Data analysis

The air sampling data were further categorized based on route (local vs highway), period of leaving (AM vs PM), onward direction (northbound vs southbound) and season (spring vs summer). Statistical software of SPSS 12.0 was used to analyze the effect of those variables on the measured pollutant levels.

3. Results and discussion

3.1. VOCs

The average concentrations of benzene, toluene, ethylbenzene, m/p-xylene, o-xylene (BTEX) and formaldehyde obtained in this study were 6.6 ± 1.9, 74.1 ± 22.5, 9.4 ± 1.8, 7.7 ± 2.3, 5.5 ± 1.6 $\mu g\ m^{-3}$ and 11.6 ± 4.5 ppb, respectively. The BTEX concentrations measured herein obviously exceeded the proposed indoor VOC guidelines for aromatic compounds (50 $\mu g\ m^{-3}$, Seifert, 1995). Table 2 shows the in-cabin VOC levels obtained in this and several previous studies. The VOCs levels obtained from the long-distance buses running on highways were generally lower than those from most of the previous